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**Price Discovery and Trading After Hours:  
New Evidence from the World's Largest Carbon Exchange**

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# **Price Discovery and Trading after Hours: New Evidence from the World's Largest Carbon Exchange\***

## **Abstract**

We investigate the impact of after-hours trading on magnitude and timing of price discovery over the close-to-close period on the world's largest carbon trading platform, the European Climate Exchange (ECX). Low volume trading in carbon financial instruments can lead to relatively high levels of price discovery but the generated pricing has low efficiency levels. This is informed by the high levels of informed trades and low levels of liquidity trades. Our results show higher trading volume per minute and price efficiency for after-hours when compared with regular trading hours. As a result of higher proportion of informed trades, adverse selection costs for trades during the after-hours are significantly larger than those for trades during the regular trading-day.

JEL Classifications: G13, G15, G18, G19

Keywords: price discovery, information asymmetry, transaction costs, informational efficiency, carbon futures, climate change policy and regulation.

## **1. Introduction**

Technological advances in financial markets since the late 1980s altered the way equity markets operate and led to studies of stock market price discovery and its determinants (see among others Barclay et al., 1990; Flood et al., 1999; Chan et al., 1995b; Easley et al., 1996; Easley et al., 1997). A particular consequence of these advances was the introduction of after-hours trading (AHT) and more specific price discovery work on this phenomenon followed. Barclay and Hendershott (2003) investigate the AHT periods of before market opens (BMO) and after market closes (AMC) on the Nasdaq, creating the first comprehensive insight into how these two periods contribute to price formation. Contributions to understanding BMO price discovery have also been made through analyses of non-executed orders and non-binding quotes prior to opening. Madhavan and Panchapagesan (2000) and

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Stoll and Whaley (1990) analyse the impact that activities of professional traders have on the opening price on the NYSE. Biais et al. (1999) and Davies (2003) investigate the effect of non-binding BMO orders on the Paris Bourse and the Toronto Stock Exchange respectively.<sup>1</sup> Ciccotello and Hatheway (2000) and Cao et al. (2000) examine the price discovery process by means of non-binding market maker quotes.

More recently, He et al. (2009) investigate the efficiency of price discovery in a 24-hour US treasury market showing that the overnight trading period is a more important component of the treasury price discovery process than previously thought. This is a clear departure from the findings of Barclay and Hendershott (2003) on contributions of overnight trades to price discovery. Jiang et al.'s (2012) analysis of AMC trading, price contributions and discovery after the release of firm earnings (during AHT), reaches the same conclusion as He et al. (2009). Confirming the influence of after hours trading, they find BMO and AMC periods contribute 36% and 60% of price discovery on announcement days despite comparatively low volumes (see also Greene and Watts, 1996).

Our contribution to the existing literature on price discovery in AHT comes from an analysis of a unique market which exchanges traded carbon permits. The European Union Emissions Trading Scheme (EU-ETS) is the world's first large experiment with an emission trading system for CO<sub>2</sub> and it is being keenly watched by policy makers in other regions throughout the world. Its success or otherwise will be a factor in determining whether a global emissions trading scheme will be adopted as a mechanism for limiting Greenhouse Gas Emissions. Our findings on price discovering during the normal trading day and AHT periods will indicate EU-ETS market efficiency, and therefore inform the case for a *market-led* approach to tackling global warming via the reduction of carbon emissions. Although a

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<sup>1</sup> Biais et al. (1999) also show how these orders reflect learning in the market.

few other papers have investigated efficiency in the EU-ETS (see for example Joyeux and Milunovich, 2010; Montagnoli and de Vries, 2010), this is the first study that investigates efficiency in the Kyoto commitment phase with respect to the intraday evolution of price discovery and trading activity.

Our results reveal that more contracts are traded per minute in the AMC period than during the normal trading day. Using the Huang and Stoll (1997) spread decomposition model, we discover that higher levels of information asymmetry are present during the AMC period/hour than at any other interval/hour during the normal trading day. We also find evidence that contribution to price discovery is a function of liquidity. Less liquid contracts prove the highest contributors to price discovery, even though they are informationally inefficient. Our analysis of exchange traded permits thus corroborates the extant literature which suggests that small amounts of trading can generate disproportionate price discovery and that liquidity leads to informational efficiency. Also, as in other studies, the least traded instruments contribute the largest proportion of price discovery in the AMC. Our findings suggest that a mandatory cap and trading scheme such as the EU-ETS can run as an efficient market for carbon financial instruments and therefore is an efficient way of reducing carbon emissions. The success of the EU-ETS in efficiently reducing carbon emissions makes a valid case for the introduction of a global mandatory market-led approach to reducing carbon emissions.

The remainder of this paper is structured as follows. In the next section we provide the background to the study by discussing the EU-ETS mechanism and summarizing the literature on price discovery and transaction costs in the EU-ETS. Section 3 discusses our sample selection and describes the data. Section 4 reports our econometric methodology and the empirical findings, and finally section 5 concludes.

## **2. Background to Study**

### **2.1 THE EUROPEAN UNION EMISSIONS TRADING SCHEME**

The EU-ETS was established in 2005 to achieve the EU's emissions reduction target under the Kyoto protocol and is the largest international cap and trade scheme by value. It currently covers about 11,500 installations in Europe. Its annual dollar volume of transactions has exceeded US\$100 billion consistently since 2008. In 2010, it topped US\$119.8 billion in value and currently drives about 97% of the global carbon market value (Linacre et al., 2011). The EU-ETS is divided into phases. Phase I ran between 2005 and 2007, it was essentially a trial phase in preparation for the Kyoto commitment phase (the so called Phase II). Phase II starting in 2008 and will run until 2012. During this phase, the EU resolved to continue with the scheme even in the absence of a global agreement to curb emissions by adopting proposals for a third phase. Phase III will run from 2013 to 2020. Table 1 outlines the major differences between the three phases (see also Daskalakis et al., 2011 for comprehensive policy and economic review of the EU-ETS).

Emission permits (European Union Allowances – EUAs) are generated electronically as records on various national registries connected to the central hub: the Community Independent Transaction Log (CITL). Annually, in April, the installations are required to submit EUAs equivalent to their verified emissions for the preceding compliance year. Project based permits are allowed for submission as well but with strict limits<sup>2</sup>.

**[INSERT TABLE 1 HERE]**

Literature on price discovery and transaction costs on exchange traded permits using high frequency field data is scarce, especially for the European carbon futures markets. Most

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<sup>2</sup> Project based permits include Certified Emission Reduction Units (CER) and Emission Reduction Units (ERU) from Clean Development Mechanism and Joint Implementation (JI) respectively.

of the contributions in this area have been on upstream issues such as initial allocation of emission permits and market conception (Convery, 2009).

Benz and Klar (2008) were the first to provide an analysis of price discovery in the European carbon futures market by investigating estimated transaction costs in Phase I (2005-2007) of the EU-ETS using intraday data. Similarly, Rittler (2011) was the first to study price discovery and causality in the early part of Phase II of the EU-ETS. Benz and Klar (2008) focus on price leadership between two *platforms* (European Carbon Exchange (ECX) and NordPool) in the EU-ETS and Rittler (2011) on price leadership between two *instruments* (spot and futures contracts). While Benz and Klar (2008) conclude that the ECX leads price discovery, Rittler (2011) shows that futures contracts lead price discovery. Using a different methodology, Cason and Gangadharan (2011) conduct a laboratory examination of price discovery in linked emissions trading markets. They find improvements in price discovery and efficiency as a result of intermediation between linked markets. This is relevant to this study because the EU-ETS has already been linked to countries outside the EU (Iceland, Liechtenstein and Norway) and EUAs created by those countries are traded on the ECX platform<sup>3</sup>.

There are several studies relating to Rittler (2011) in its examination of links between the spot and futures contracts. Uhrig-Homburg and Wagner (2007) employ daily data from Phase I to determine price discovery measures for both spot and futures. The study concludes that futures lead the price discovery process. Daskalakis and Markellos (2009) and Daskalakis et al. (2009) explore the links between spot and futures by modelling EUA price dynamics using stochastic processes in Phase I. They find that inter-phase banking restrictions lead to inconsistencies in futures pricing during Phase I. Futures pricing only

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<sup>3</sup> Linking in the context of the EU-ETS also refers to the acceptance of Kyoto project allowances in the EU-ETS.

conforms to the cost of carry model on intra-phase basis only. This conclusion is supported to some extent by Joyeux and Milunovich (2010) since they show that long-run links exist between spot and futures in Phase I. Mizrach and Otsubo (2011) examine the onset of price discovery on the Bluenext spot market in Paris and the ICE/ECX futures market in London, the two largest platforms in the EU-ETS. They report that about 90% of the price discovery in the EU-ETS takes place on the ECX. Their results which are based on data from Phase II of the EU-ETS confirms the results of Benz and Klar (2008) who employ data from Phase I of the scheme. Our study differs from the aforementioned studies in that we focus on efficiency in relation to the intraday evolution of price discovery and trading activity. Also recently, Frino et al. (2010) examine liquidity and transaction costs in the EU-ETS using intra-day data from the ECX, and Ibikunle et al. (2011) employ event study methodology with the market model and liquidity proxies to investigate liquidity and trading improvements arising from the transition to Phase II using daily data from the European Energy Exchange (EEX). Both studies concur that liquidity in the EU-ETS has advanced since the start of the second phase of the scheme.

### **3. Data**

#### **3.1 THE TRADING ENVIRONMENT ON THE ECX**

Trading in physically delivered EUA futures commenced in April 2005. The contracts are offered on a quarterly expiry cycle (March, June, September and December) up to December 2014. Futures with annual (December) deliveries for up to 2020 were recently introduced. The underlying for each ECX EUA contract is 1,000 EUAs. The trading system is electronic and continuous, initiates at 7:00hrs and ends at 17:00hrs UK local time from Monday to Friday. In 2010, EUA carbon permits accounted for more than 84% of global



carbon market value. Of these, 73% are traded as futures contracts (see Kossoy and Ambrosi, 2010; Linacre et al., 2011). The ECX platform is the market leader in EU-ETS exchange based carbon trading with more than 92% market share. Over-the-Counter (OTC) trades are sometimes registered on the platform to reduce counter-party risk. The December maturity contracts represent about 76% of daily transactions on the platform hence form the basis of our investigations. The global dominance of the ECX platform has attracted participants from beyond Europe. In 2009, about 15% of trade volume on the platform was from traders domiciled in the United States (Kossoy and Ambrosi, 2010).

Carbon Financial Instruments (CFI) trading in the ECX is done electronically and anonymously on the Intercontinental Exchange (ICE) platform. Executed orders go through the Trade Registration System (TRS) for account allocation.

There is a pre-open trading period of 15 minutes to allow participants place early orders in preparation for the trading day<sup>4</sup>. When trading closes at 17:00hrs no officially sanctioned trade is no longer allowed; however allowance is provided for registering of Exchange for Physical (EFP) and Exchange for Swaps (EFS) trades<sup>5</sup>. This can be reported using an electronic facility called the *Iceblock* on the platform. The Exchange officially requests that these trades be registered up to 30 minutes after the close of official trading each trading day except for the day of expiration of the traded contract. Reporting of EFP/EFS trades on the exchange however occurs up until about 6:00pm regularly on the days covered by our sample<sup>6</sup>. They are essentially bilateral trades that in theory require no market maker quotes to execute.

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<sup>4</sup> This 15-minute period on the ECX platform recorded few executed orders over the ten-month period covered by our data in 2009 (February-November), only 12 trades with a combined contract volume of 700 were recorded on the exchange. The dates, times and corresponding volumes are available on request.

<sup>5</sup> EFP and EFS trades are only permitted for EUA and CER Futures contracts.

<sup>6</sup> This extension of registration period for EFP and EFS trades is acknowledged by ECX.

The buyer who charges the trade to the seller usually registers the trades. The seller then matches the trade by confirming it (*Non-crossed Trade*). It is possible for prices of EFP and EFS trades during the AMC period to fall outside the high and low points in the normal trading day (or beyond the biggest price shift from the previous close's settlement price) since the prices are not revealed until after the close. However, this requires approval from the ECX Futures Europe Compliance Department prior to registration. The maximum price movement however is still pegged at €1.00.

### 3.2 SAMPLE SELECTION

We use two datasets, both obtained from ICE Data LLP, for our analysis. The first, which is the main dataset we use, comprises of all intra-day tick-by-tick ECX EUA Futures contracts trades on the ECX platform from February 2009 through November 2009. The dataset contains date, timestamp, market identifier, product description, traded month, order identifier, trade sign (bid/offer), traded price, quantity traded, parent identifier and trade type. The variables are for 15 carbon financial instruments (CFI) (futures contracts and futures spreads).

The second dataset is the end of day (EOD) data for ECX Futures from February 2009 through November 2009. From here, we obtain the daily settlement price, daily low price, daily high price, and daily first price. We also extract daily volume (for all trade types) and daily weighted average price. This dataset does not contain any records for futures contract spreads, which are present in the first dataset.

In order to improve the robustness of our findings, we eliminate 11 of the CFI available by applying the following conditions:

1. Both datasets must provide trading records from February 2009 through November 2009 for the selected CFI.
2. As the analysis is based on the comparison of normal trading day to AMC, the CFI must be tradable during both periods in an EFP or EFS trade.
3. The CFI must also be traded for at least 20% of days during both periods between February and November, 2009.

The ECX tick dataset includes the trade sign identifier, hence we could identify the trades as buyer or seller initiated. For the AMC trades however, the challenge is that all trades are identified as buyer initiated by default since the trades are usually registered by the buyer who then alleges it to a seller. This is misleading; hence to overcome this problem, we use the tick test for classifying the trades<sup>7</sup>. We classify trades at a price greater than the prevailing trade midpoint as buyer initiated and those at a price lower than the prevailing midpoint as seller initiated. If the current and the previous trades are the same price we classify using the next previous trade. Analysis of the tick rule by Lee and Ready (1991) and Aitken and Frino (1996) suggest the tick rule's accuracy to be in excess of 90%. Aitken and Frino (1996) however suggest a lower accuracy level of 74% in some cases. Finally, we exclude the 12 trades recorded before 7:00hrs London time in the sample.

### 3.3 SAMPLE DESCRIPTION

The ECX platform is the only exchange where official AMC trading is recorded in the EU-ETS and the trading is quite thin, averaging approximately 61 trades and 2,675 contracts per day. The contracts in our sample represent about 99% of total AMC trades recorded on

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<sup>7</sup> For robustness we compare results based on tick test and actual identifier codes for the normal trading day trades. The results are substantially the same.

the platform between February and November 2009. Trading in the EU-ETS in comparison to more established financial and commodities derivatives markets, is also thin. AMC trades averaged €37 million in value per day or 17% of the normal trading day's value between February and November 2009<sup>8</sup>. AMC recorded trading is limited to between 17:00 and 18:00 hours GMT.

In Table 2 we report on normal trading day and AMC trading activity. Our results show daily average estimates for individual contracts and the full sample averages per contract per day. The trading volume is skewed towards one contract (December 2009) throughout the 211 days covered by our study. About 83% of the AMC trades in our sample are for the December 2009 contract. This is not unusual in the EU-ETS. Ibikunle et al. (2011) report that the December contract with the closest maturity date is the most actively traded on the platform. Joyeux and Milunovich (2010) as well as Mizrach and Otsubo (2011) also report the same phenomenon for the ECX.

The most traded contract, the December 2009, averages 50 AMC trades per day (with a market value of approximately €26 million per day), while the other three contracts in our sample account for an average of ten trades (worth approximately €10.73 million) per day. Trading activity for the lower trading contracts shows a steep fall to an average of about 7 contracts per day for the closest trading one (December-2010) to the December-09 contract<sup>9</sup>.

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<sup>8</sup> As noted by Porter and Weaver (1998), large transactions executed on the Nasdaq were posted late (after-hours) after having been trading during the normal trading day. This does not hold for our sample as the trading system is electronic and the participants have real time access to input their trades at anytime during the normal trading day.

<sup>9</sup> The highest trading instrument not included is the December-2013 futures contract. It has an average of less than 0.12 trades recorded AMC and 1.09 during normal trading hours, for the period covered by this dataset there are only 258 trades. As a result of this extremely low level of market activity, we do not include the contract and others with lower trading AMC activity in the analysis.

[INSERT TABLE 2 HERE]

## 4. Results and Discussion

### 4.1 TRADING VOLUME AND VOLATILITY

Figure 1 depicts for each half-hour interval, the average daily trading volume and average return volatility. Trading on the ECX displays an inverted S-shape rather than the familiar U-shape identified with derivative markets (see for example Chan et al., 1995a; Gwilym et al., 1997). Also in a clear contrast to previous studies, the most active period during the normal trading day is *not* the opening period. The closing stages of the normal trading day and the one hour AMC period are the most active periods on the ECX with respect to trading volume. Indeed, the largest Euro volume of trades per half-hour is recorded in the first half hour of AMC trading. This volume then holds steady for the concluding half-hour of the AMC trading period shedding only about 11.62% of volume from the preceding half-hour period. Volatility and trading volume display high levels of correlation (Spearman's Rank Correlation Coefficient of 0.74)<sup>10</sup>.

[INSERT FIGURE 1 HERE]

While the AMC trading volume on the ECX platform is inconsistent with previous studies (see for example Barclay and Hendershott, 2003), larger AMC mean and median trade values are consistent with them. Figure 2, shows log-transformations of median and mean trade sizes at one-minute intervals<sup>11</sup>. We observe a very steep rise in the mean and median sizes of trades after the close as expected. Figure 2 shows the mean estimates quadruple in the first minute of AMC trading and then peak at almost €955,000 on 17:07hrs.

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<sup>10</sup> Volatility was estimated using the December 2009 contract only due to large gaps in trading cycle of other contracts. We also calculated volatility using the other contracts but excluded the gap periods. The results are similar.

<sup>11</sup> These are plotted on a log scale because of the large variability of the trade sizes after-hours.

Trading values during the remainder of the session hold up competently. The final minute of trading has a mean value of nearly €600,000 which is almost twice the highest mean estimate at any point during the normal trading day.

**[INSERT FIGURE 2 HERE]**

#### 4.2 MOTIVATION FOR TRADING AMC: LIQUIDITY OR INFORMATION?

Platform rules governing the registration of EFP/EFS trades on the ECX during the normal trading day and the AMC are basically the same. Trading in the AMC is however open only to members with access to the *Iceblock* facility. Platform membership is usually for professional traders. Based on this, it is expected that the market at that time will be primarily composed of professional traders or traders acting on behalf of their clients. The question then arises, why leave it that late? Why is the largest value of trading per minute reserved for this period of the day? EFP and EFS trades can be reported at anytime of the day with less of the time constraint that is the one-hour AMC market.

Microstructure studies identify two main types of traders, both holding idiosyncratic risks: the first type trades in search of liquidity, their aim is inventory control and portfolio rebalancing (especially at the end of the normal trading day). The second type trades on private information unknown at the time of trading to majority of the market. Since participation in the market is motivated by different reasons, we suppose these two classes of traders will have varying degrees of activeness in the AMC session.

According to market microstructure literature, information asymmetry and uncertainty over fundamentals usually decrease over the course of a trading day<sup>12</sup> (see Kyle, 1985; Madhavan et al., 1997; Foster and Viswanathan, 1990; Easley and O'Hara, 1992; Easley et al., 1997; Huang and Stoll, 1997). Barclay and Hendershott (2003) note that public and private

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<sup>12</sup> Madhavan et al. (1997) also find that trading costs increase as the normal trading day progresses.

information accrue overnight when no trading takes place. Indeed, for the ECX there is a non-trading interval of 12 hours and 45 minutes between the end of the AMC market and the 15 minute pre-open at 6:45hrs London local time. This interval is longer than the 11-hour 15-minute combined trading period afforded by the platform. It is reasonable to assume that carbon market information could have accumulated during the no-trading period; hence we expect high information asymmetry in the early trading period and expect this to decline during the day.

Further, the EU-ETS is an unusual market with many twists and turns fuelled by the controversy that surrounds climate change science. Many trades aim to offset emissions by market participants and so are based on information on *anticipated* levels of emission. Emissions are ultimately determined by installation production levels, and so we expect the AMC period to be dominated by informed trades and the more informed of these trades are likely to be in the later maturity contracts.

Emission permits are not submitted year-round to offset verified emissions positions, therefore trades could also be based on risk hedging and portfolio diversification. If emission permits are for submission to the authorities once a year, it is logical to expect that AMC trading is not an absolute necessity unless there is an advantage to be earned. Uhrig-Homburg and Wagner (2009) argue along these lines in a study investigating the EUA spot and futures relationship. Much more importantly, the size of the typical EFP/ EFS trades in our sample suggests that these trades will be mainly initiated by institutional and compliance traders who are clearing members of the exchange. Kurov (2008) finds evidence that institutional traders in index futures markets are more informed than other classes of market participants. These reasons lead us to expect larger spreads and higher levels of informed trading during the

AMC<sup>13</sup> than the normal trading day. Previous studies have also shown there is higher informed trading during AMC than during normal trading day (see for example Barclay and Hendershott, 2003).

The motivation for trades in search of liquidity will be different to the motivation for trades influenced by privately held information. According to Brock and Kleidon (1992), being in possession of a sub-prime portfolio overnight comes at higher costs in comparison with holding an optimal one. This provides a strong motivation for market participants who could not complete the optimal balancing of their portfolio during the regular hours to trade in the AMC period. On the ECX, the EFP and EFS trades offer this opportunity.

In addition to expecting higher informed trades in the AMC, we also expect that the first few hours of the normal trading day will exhibit higher information asymmetry than other periods during the normal trading day. This is as a result of the information accumulation we expect to have occurred during the non-trading period overnight. As a result of reduced number of individual trades (see Table 2), perhaps due to the reduced number of participants trading in the AMC period, we also expect larger spreads than at any interval during the normal trading day during the AMC period. The superior euro value and contract sizes of the trades in the AMC (Figures 1 and 2) suggest that a substantial proportion of the trades are information-induced hence there will be the imposition of larger spreads in order to compensate for risk of trading with in this period.

We now examine the hypothesis that there is a higher level of informed trading and larger spreads during the AMC trading hour than at any other period during the day by estimating adverse selection components and one-half effective spreads at different intervals

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<sup>13</sup> Reasons already identified for the EFP and EFS trades may not suffice here as the trades could easily be executed during the normal trading day.



during the day and during the AMC period by using Huang and Stoll's (1997) spread decomposition model.

The model decomposes the bid-ask spread into the adverse selection and inventory cost components by using buying and selling pressure. The technique is based on the fact that changes in quotes due to inventory are not just dependent on inventory changes in one financial instrument but others as well (induced serial correlation in trade flows). Huang and Stoll (1997) assume that adverse information is instrument specific but inventory effects are idiosyncratic (in relation to the portfolio held by market participants)<sup>14</sup>. This model has been established by other market microstructure studies (see among others Van Ness et al., 2001; Heflin and Shaw, 2000)<sup>15</sup>.

We estimate Equation (1) for each contract and each interval separately using the ordinary least squares and time series regression as adopted by Heflin and Shaw (2000)<sup>16</sup>.

$$\Delta P_{k,t} = \beta_{1,k} Q_{k,t} + \beta_{2,k} Q_{k,t-1} + \beta_{3,k} Q_{A,t-1} + e_t \quad (1)$$

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<sup>14</sup>This approach models market participants as adopting a portfolio view when executing inventory modification of stocks. It is hinged on the Ho and Stoll (1983) model that shows the connection between quote shifts in a stock and inventory changes other stocks. The authors prove that the quote shifts in stock  $a$  which is in reaction to a transaction in stock  $b$  is contingent on  $cov(R_a, R_b)/\sigma^2(R_b)$ .

<sup>15</sup> Van Ness et al. (2001) suggest that the Huang and Stoll (1997) model is superior to other commonly used models in measuring adverse selection information costs. However, the "superiority" of the model has its costs. Some authors have reported the possibility of obtaining implausible estimates from the model estimation when using the probability of trade reversal approach in place of trading pressure approach. For example Clarke and Shastri (2000) report this problem analysing a sample of 320 NYSE firms, indeed Van Ness et al. (2001) also report similar issues. It seems that there is a correlation between low probability of trade reversal and the implausible estimates. For this paper we report only the trade aggregator estimation and there is no evidence of this problem since our estimates are comparable to those of Benz and Klar (2008) estimated using the Madhavan et al. (1997) model.

<sup>16</sup> Huang and Stoll (1997) point out that the cross-sectional estimation of Equation (1) usually overestimates the adverse selection costs component of the spread. By adopting a time series estimation of Equation (1) for each contract we avoid this issue.

Where  $\Delta P_{k,t}$  is the change in price from the previous retained trade,  $Q_{k,t}$  is equal to 1 (-1) when the transaction at period  $t$  for contract  $k$  is a sell (buy) and  $Q_{A,t-1}$  is the aggregate buy-sell indicator variable used in encapsulating portfolio trading pressure on market participants inventory levels. It is measured as:

$$\begin{aligned} Q_{A,t-1} &= 1 \text{ for } \sum_{k=1}^n Q_{k,t-1} > 0 \\ Q_{A,t-1} &= -1 \text{ for } \sum_{k=1}^n Q_{k,t-1} < 0 \\ Q_{A,t-1} &= 0 \text{ for } \sum_{k=1}^n Q_{k,t-1} = 0 \end{aligned}$$

Where  $n$  is the number of contracts in our sample trading during that interval.

We follow Huang and Stoll (1997) in employing only the last trade at every five-minute interval to formulate the variables in equation (1)<sup>17</sup>. Huang and Stoll (1997) observe that large trades are sometimes broken up and registered as smaller trades. To counter the problems that may arise from this, they employ a “bunching” technique whereby trades occurring within five minute intervals of each other executed at the same price and with same quotes are bunched together and regarded as one trade. The results obtained by Huang and Stoll (1997) from the bunching technique suggest that the method increases the adverse selection component estimates<sup>18</sup>. As devised in Equation (1), the  $\beta_{1,k}$  estimate is one-half the

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<sup>17</sup>For the normal trading day, we estimate equation (1) using the trade classification provided by ECX in our dataset and also by employing the tick rule (Lee and Ready, 1991). The empirical estimates from both methods show quantitatively similar results and return a correlation coefficient in excess of 0.97. We therefore employ the results based on the tick rule in our results for both normal trading day and AMC periods.

<sup>18</sup>We also employ an estimated trade reversal probability in place of the aggregate buy/sell indicator but as is evident in the results of Huang and Stoll (1997), the method is disposed to giving negative adverse selection components. We do not report the estimates from this method but instead use the aggregate indicator.

estimated effective spread and, the adverse selection component is equivalent to  $2(\beta_{2,k} + \beta_{1,k})$ . We use the Wilcoxon-Mann-Whitney test for obtaining statistical inference on the level of differences between normal trading day intervals and the AMC period.  $\square$

In Panel A of Table 3, we report the estimated adverse selection costs components of the effective spread for each contract and time interval as well as the combined contracts average. The results largely support the hypothesis on reducing information asymmetry over the course of the normal trading day. In the normal trading day, information asymmetry is highest in earlier intervals. Overall, it is highest between 7:00hrs and 11:00hrs than at any interval during the rest of trading day. As expected there is a high level of information asymmetry after the close to support the suggestion that those who trade in this market do so based on private information. Our results are also consistent with earlier studies finding higher levels of informed trading in the AMC period than during the normal trading day (see Barclay and Hendershott, 2003; He et al., 2009; Jiang et al., 2012). The average adverse selection spread component for all contracts during the AMC is almost 12 times the value for the normal trading day (07:00-17:00). This implies that participants are significantly more likely to trade with private information in the AMC market than during the normal trading day. Although the investigations on information asymmetry is conducted in a relatively less active and quite unusual market, our adverse selection costs and one-half effective spread estimates in the normal trading day period are comparable to estimates from most previous studies (see among others Heflin and Shaw, 2000; Huang and Stoll, 1997; Madhavan et al., 1997; Lin et al., 1995; George et al., 1991; Glosten and Harris, 1988).

In Panel B, we present the one-half effective spread estimates. The results confirm our hypothesis that spreads are wider in the AMC period than in the normal trading day. The results in the normal trading day are also comparable to the results obtained by Benz and Klar (2008) using the Madhavan et al. (1997) model to estimate half spread in the ECX during

Phase I of the EU-ETS. All the one-half effective bid-ask spread estimates are statistically significant at all conventional levels, with the exception of the December-2012 contract. Spreads are generally higher during the first two hours of trading than at any other period during the normal trading day.

**[INSERT TABLE 3 HERE]**

#### 4.3 PRICE DISCOVERY; INFORMATION ABSORPTION ON THE ECX

It is established in the literature that price discovery is a function of trading activity; (see among others Jiang et al., 2012; Pascual et al., 2004; Kim et al., 1999; French and Roll, 1986). In sub-section 4.2 we demonstrate that information asymmetry is higher during AMC session than during the normal trading day. We also show that spreads grow larger in the AMC period as well. This implies that there should be a higher proportion of price discovery per hour taking place during the AMC. Results obtained during the open-close period by Barclay and Hendershott (2003) suggest that the least trading instruments contribute the higher proportion of price discovery during the regular trading hours. In Table 2 we show that the December-2011 and December-2012 contracts are the least trading, we therefore expect that they will contribute the highest ratio of price discovery during the normal trading period. We thus examine this and the relatedness of the distribution of informed trading to price discovery in this sub-section using two price contribution measures: The weighted price contribution (WPC) and the weighted price contribution per trade (WPCT).

##### 4.3.a *Weighted Price Contribution*

We use the WPC established by previous studies (see for example van Bommel, 2011; Cao et al., 2000; Barclay et al., 1990; Barclay and Hendershott, 2004; Barclay and Warner,

1993)<sup>19</sup> as our measure of price discovery. We compute the contribution of different EUA futures contracts to the price discovery process during five intervals of the normal trading day and the one hour AMC period. We also include in our measurements the estimates for the entire normal trading day period (07:00-17:00hrs London local time). The terminal period for the normal trading day is the last trade at or before 17:00:00hrs and the AMC period as the first trade after 17:00:00hrs. The WPC measure we use estimates the proportion of the 24-hour (close-close) EUA contract price return that takes place at that period.

For each contract, we define the WPC for each 24 hour period and each period  $k$  as:

$$WPC_{k,c} = \left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times \left( \frac{ret_{k,c}}{ret_c} \right) \quad (2)$$

Where  $ret_c$  is the close-to-close return for contract  $c$  and  $ret_{k,c}$  is the log-return for period  $k$  and for contract  $c$ . The intuition behind the WPC is that  $\frac{ret_{k,c}}{ret_c}$  is measure of relative proportion of the day's return provided by contract  $c$  and  $\frac{|ret_c|}{\sum_{c=1}^C |ret_c|}$  is the weighing factor for each contract. It ensures that values with smaller  $|ret_c|$  are given small weight. Thus, we compute WPC for each contract and each interval, then average across days to obtain the WPC for each contract-specific interval. We also report the WPC across all the contracts. This is defined as:

$$WPC_k = \sum_{c=1}^C \left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times \left( \frac{ret_{k,c}}{ret_c} \right) \quad (3)$$

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<sup>19</sup> van Bommel (2011) analyse three estimators of price discovery and identifies the WPC as consistent. It is also the only unbiased and asymptotically normal measure for price discovery.

Normally the WPC is computed instrument by instrument and then averaged out across the instruments (see Cao et al., 2000). When this is the case however, instrument correlations generated by the common constituent in the returns makes statistical inferences a complex affair using the mean WPC. Since we report WPC individually for each contract we need not be concerned about this; we thus employ the standard t-statistic to test the null that the daily WPC values (per period and for each contract) are not significantly different from zero. We also use the Wilcoxon-Mann-Whitney test for obtaining statistical inference on the level of differences between normal trading day intervals and the AMC period.

Table 4 shows the WPC estimates for the 24-hour (close-to-close). The results show that the most liquid contract (December-2009) contributes the least to price discovery over the entire trading periods. Results in Table 4 also confirm that the December-2012 and the December-2011 contracts are the two highest contributors to price discovery over all the trading periods (55% and 31% respectively). Together they account for 86% of total price discovery over the entire periods. Their contributions over the combined normal trading day period (07:00-17:00hrs) and the AMC period are statistically significant. This is not surprising because EU-ETS trading, as explained in section 2, is dependent on information relating to emission levels, political and regulatory shifts on environmental legislations and global treaties. In this context, the likely primary motivation for taking a position on a contract with maturity about three years away is possession of information that this is a good move either for hedging or otherwise. The distribution of price discovery also correspond to that of information asymmetry (Table 3), confirming that the contracts with the largest adverse selection costs and trading spreads contribute the higher proportion of price discovery in a market. Overall, most of the price discovery takes place during the normal trading day over a 10-hour period. However more than a quarter of the price discovery occurs

during the space of just one hour (17:00hrs-18:00hrs) in the AMC trading period, despite reduced number of executed trades.

Another important observation is that more than 21% of the total close-close price discovery occurs in the first two hours (07:00hrs-09:00hrs) of the normal trading day. This is interesting considering the fact that only about 18.9% volume of trades for all intervals occur during this period. Moreover, more than 88.13% of these trades are in the December-2009 contract which by the way, contributes nothing to price discovery during that period. Effectively, only about 16.65% of the 62,872 trades taking place at this time in our sample hold significant price information. This explains why the WPC value is not significantly different from zero. This trend is consistent with the one discussed in sub-section 4.2. The hypothesis that there is an accumulation of information during the non-trading 13.5-hour period therefore holds for the later maturity contracts. Based on this we expect individual trades in the opening period to contribute more to price discovery than at any other period during normal trading day. Our expectation here does not include the AMC because although the period enjoys the highest euro volume per minute of trade, the aggregate number of trades is vastly inferior to those in the normal trading day making the trades in the AMC potentially more informative than those in the opening period. We test this hypothesis in sub-section 4.3.b below. We must point out that price discovery estimates in the 15:00-17:00 period are quantitatively similar to the morning period's and are statically significant. This is down to the rising level of EFP/EFS trades during this period (also seen in Figure 1). As the normal trading day draws to a close, traders start to push their trades in order to ensure their portfolios attain optimal status or to avoid trading with the potentially well informed traders in the AMC.

We observe that the lowest average WPC during the periods is recorded during the 11:00-13:00hrs range. In Figure 1, this period has the highest volatility relative to trading

volume. The high volatility and low WPC raises the suggestion of noisiness during the normal trading day. In sub-section 4.4, this issue will be examined closely by analysing the efficiency of the price discovery process.

**[INSERT TABLE 4 HERE]**

#### 4.3.b *Weighted Price Contribution per Trade*

The high WPC estimate recorded for the first two hours (07:00-09:00hrs) of the normal trading day coupled with the level of trading in comparison with the other normal trading day intervals provide the basis to expect high information content per trade for the later maturity contracts. This is because the bulk of the price discovery reported for the 07:00-09:00hrs period is contributed by them. And since they only account for 17% of the trades during the period, the price discovery per trade values for their individual trades are expected to be significant. The adverse selection component is also highest during this period for the normal trading day. We therefore proceed to examine the information content per trade using the WPCT measure. We divide the WPC per contract and for each trading interval with the weighted ratio of trades executed for that contract and during that period. If for each day,  $t_{k,c}$  is the number of executed trades in time period  $k$  for contract  $c$ , and  $t_c$  is the total sum of  $t_{k,c}$  for all the periods, then  $WPCT_k$  is defined as

$$WPCT_{k,c} = \frac{\left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times (ret_{k,c}/ret_c)}{\left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times (t_{k,c}/t_c)} \quad (4)$$

As a consequence of the measure outlined in equation (4) being equivalent to a ratio of the aggregate price shift occurring in an interval scaled by the ratio of trades in that same interval, the WPCT should be about one. This holds only if we assume that all trades carry



similar levels of information to the market. We report the WPCT close-to-close price shift in Table 5. For statistical inference, we use the standard t-statistic to test the null that the daily WPCT values (per period and for each contract) are not significantly different from zero. We also use the Wilcoxon-Mann-Whitney test for obtaining statistical inference on the level of differences between normal trading day intervals and the AMC period.

Our results show that for three of the contracts, the trades in the opening period hold higher levels of information than at any time during the normal trading periods. Some of the estimates for the normal trading day are noisy as they are not statistically significant. Consistent with Panel A of Table 3 and Table 4, on per contract basis, the contract with the farthest maturity, the December-2012 contract holds the highest level of information per trade. We also observe individual trades in the period 15:00hrs-17:00hrs are very informative and are largely statistically significant across all contracts. This corresponds to WPC estimates in Table 4 being high and significant during this interval. The informed trading effect of the increasing EFP/EFS trades at this period is therefore more evident as the proportion of liquidity-seeking trades during the normal trading hours start to taper off. This implies that the level of price discovery reported for this period will have a level of efficiency comparable to that of the AMC period; we examine this in sub-section 4.4. The results in sub-section 4.3 (Tables 4 and 5) thus confirm that the AMC, the opening two hours and the two hours prior to closing are very important in the price discovery process.

**[INSERT TABLE 5 HERE]**

#### 4.4 EFFICIENCY OF PRICE DISCOVERY: ANALYSIS BY PERIOD

In markets with relatively low trading volumes like the EU-ETS platforms, big liquidity induced trades usually lead to short term price effects that are afterwards reversed. This is because large trades are commonly considered as being information-driven. Although,

on per minute basis, the highest proportion of large contract trades are in the AMC; results shown so far suggest there is a higher proportion of liquidity-driven trades in the normal trading day than in the AMC. Based on this we expect the normal trading day trades to be generally noisier than the AMC trades because of price reversals.

However, since large spreads, as shown in Panel B of Table 3 for the AMC period, are typically instrumental to price reversals, we also suspect there may be an appreciable level of noisy trades in the AMC. Hence our hypothesis here is for lower signal: noise ratio for the normal trading day than the AMC. Based on foregoing analysis, we also expect the December-2011 and December-2012 (the most illiquid instruments in our sample) to generally have low signal: noise ratio, implying high noise levels across all periods. In subsection 4.3, we observe that the high volatility levels and low WPC estimates around the 11:00-13:00hrs interval indicates noisy trades; hence we expect the lowest signal: noise ratio estimates in the normal trading day for this interval.

We measure price efficiency by using the so-called *unbiasedness regressions* (as shown in equation 5) to estimate the noisiness of contracts' prices for different intervals (Biais et al., 1999).

$$ret_{cc} = \alpha + \beta ret_{ck} + \varepsilon_k \quad (5)$$

For each contract  $\square$  and each day equation (5) is estimated separately for each time interval (60 minutes each for the normal trading day and 10 minutes for the AMC), where  $ret_{cc}$  is the close-to-close return and  $ret_{ck}$  is the return from the close to the end time of interval  $k$ .

$\square$  Barclay and Hendershott (2003) argue that the slope coefficient  $\beta$  is a measure of signal: noise ratio of trades. Reviewing the regression analysis problem of standard errors-in-

$\square$

variables, assuming contracts returns are accurately computed and they are not correlated, the slope coefficient will equal one. Then take the assumption that the actual return is not observed and also that the observable return is actually equivalent to the real return plus the noise. Noise in this sense refers to microstructure impacts such as spread components or reversible price effects. If we imagine that  $ret_{cc} = RET_{cc} + v$  and  $ret_{ck} = RET_{ck} + u$ , then we can consider  $RET_{cc}$  and  $RET_{ck}$  as the actual returns and that  $u$  and  $v$  have zero mean and respective variances equivalent to  $\sigma_u^2$  and  $\sigma_v^2$ . An ordinary least squares estimation of Equation (4) will result in the estimated slope coefficient  $\beta^*$ , where

$$\beta^* \xrightarrow{p} \beta \left( \frac{\sigma_{RET_{ck}}^2}{\sigma_{RET_{ck}}^2 + \sigma_u^2} \right)$$

$\sigma_{RET_{ck}}^2$  is a measure of the total information observed from the previous close to the time period  $k$  and  $\sigma_u^2$  is the noise effect observed in prices at interval  $k$ . The slope thus measures the ratio of information content (signal) to signal plus noise in prices at interval  $k$ .

Specifically, we conduct a time series estimation of Equation (5) for each contract and each time period. We obtain the slope coefficient estimates for each contract and calculate the mean for all contracts and for each interval. Following Biais et al. (1999) and others<sup>20</sup>, we calculate confidence bands using the time series' standard errors for the mean of the slope coefficient estimates. As pointed out by Biais et al. (1999) time series estimation of instrument returns in the presence of learning is problematic as a result of learning-induced non-stationarity. This is relevant to our analysis, especially since we analyse learning in the after hours market. To ensure that our analysis does not suffer from the spurious regression

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<sup>20</sup> See Fama and Macbeth (1973) and Barclay and Hendershott (2003).

problem, we conduct individual unit root tests of each time series variable used in the separate regressions. The test results suggest that the variables are stationary. To obtain robust t-statistics, we apply the Newey and West (1987) heteroscedasticity and autocorrelation consistent covariance (HAC) matrix estimator<sup>21</sup>. The Newey and West (1987) HAC is consistent in the presence of both heteroscedasticity and autocorrelation of unknown form. The results obtained using the HAC estimator are very similar to those obtained using only OLS and in some cases have stronger levels of statistical significance for corresponding coefficient estimates.

Figure 3 shows the graph of the mean slope coefficients with the confidence bands. In Table 6 are also two panels of the slope estimates for the normal trading day periods and AMC periods. Comparatively, the signal: noise ratio in the normal trading day is generally lower than the AMC as we hypothesised. During the normal trading day, the signal: noise ratio range from about 0.37 to 0.78 and from 0.61 to 0.92 in the AMC, clearly indicating the normal trading day as noisier. Ciccotello and Hatheway (2000) and Barclay and Hendershott (2003) find high signal: noise ratios that are sustained through the normal trading day for the NASDAQ pre-open in 1996 and 2000 respectively (NASDAQ pre-open in 2000 daily averaged more than \$2million). Biais et al. (1999) instead find low signal: noise ratio for the Paris Bourse that has no official pre-open trading in 1991. Orders are allowed in the pre-open but no execution takes place in 1991 on the Paris Bourse, hence no volume is registered although the last 10 minutes before the normal trading day begins is the most active period for order placement in the day. These facts and our results further confirm the generally held view that trading volumes form a vital component of efficient price discovery, especially in thin markets like the EU-ETS platforms. Indeed the highest Euro volume trading periods of

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<sup>21</sup> The Newey and West (1987) HAC is consistent in the presence of both heteroscedasticity and autocorrelation of unknown form.

the day in our sample post the highest signal: noise ratios. The view that trading activity informs price discovery is further strengthened by the fact that low signal: noise ratio is more likely for the AMC than the normal trading day because of proximity to the market close<sup>22</sup>. We conclude that higher euro trading volumes lead to higher price efficiency and that it holds more significance in thin markets.

Also our expectation of the 11:00-13:00hrs period is confirmed. The noisiest point of the day according to Figure 3 is at 13:00hrs as a result of the noisiness of price in the less liquid contracts (December-2012, December-2011 and December-2010). The December-2012 contract during this period is a lowly 0.054; underscoring the fact that majority of the trades in this contract are very noisy. The estimates suggest that the less liquid a contract is on the ECX platform the higher the likelihood of its prices being noisy. The curious case of the 11:00-13:00hrs could also be explained as some form of *lunch-time* effect. The interval falls on the period when many traders go away from their desks for lunch in the city of London. The noise level and price discovery efficiency on the ECX is however acceptable since the December-2009 (the nearest maturity) contract which accounts for more than 81.65% of all trades in the sample used achieves a very high level of price discovery efficiency.

### **[INSERT FIGURE 3 HERE]**

The regression estimates for both the normal trading day and the AMC are obtained using the same close-close returns and should therefore be correlated. This means the level of statistical difference between the AMC and the normal trading day will be biased using the time series standard errors in Figure 3. To draw statistical inference on the distinction

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<sup>22</sup> Alternate analysis run by Barclay and Hendershott (2003) on the NASDAQ however suggests this is unlikely; still it is a possibility that provides an additional basis for our argument on the link between trading volume and price discovery efficiency.

between the slope coefficients we have to consider this level of contemporaneous correlation. We follow Barclay and Hendershott (2003) method of computing for every day the difference between the normal trading day and AMC coefficients and employ the standard error of this time series to draw inferences on the difference between the two periods. Our results show that the signal: noise ratio was significantly higher in the AMC than the normal trading day<sup>23</sup>.

**[INSERT TABLE 6 HERE]**

## **5. Conclusion**

The EU-ETS was developed as the principal policy instrument to achieve the EU's obligations under the Kyoto protocol. The scheme has grown to become the world's largest carbon market and accounted for 96.46% of global allowances trades in 2009<sup>24</sup>. Several other industrialised countries that are obliged to reduce their carbon emissions as a result of their Kyoto protocol commitments have already developed similar schemes. Considering its success so far, it is reasonable to assume that in the event that it occurs, a global mandatory carbon cap and trade scheme will be based on the EU-ETS model. If the EU-ETS is to serve this purpose, there must be evidence of its efficiency.

In this paper, we test whether the EU-ETS is efficient by analyzing the association between trading volumes of permit contracts in the EU-ETS and their contribution to price discovery and informational efficiency, using intraday data. We discover that the more liquid permit instruments are, the higher the likelihood they can be traded efficiently. The price discovery process for relatively liquid instruments shows levels of efficiency comparable to those of traditional financial instruments. This is the case during both the normal trading day and AMC periods. This is a strong indication of the level of efficiency and maturity of the

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<sup>23</sup> We have not reported these results, but they are available on request.

<sup>24</sup> This figure is based on value of carbon instruments traded on cap and trade schemes. The total global value for this period was \$122.8billion.

EU-ETS. The efficiency of the EU-ETS can therefore provide a basis for the introduction of a global mandatory cap and trade scheme. An important point to note is the higher per minute level of euro trading value in the AMC. This as a result of the high concentration of informed trades or trades aimed at achieving optimal trading portfolio before the next normal trading day session. This is a viable indication of an emerging level of sophistication in this fast growing market. For policy makers, this acknowledgement is key as yet another country, Australia passes legislation for its ETS. The Australian ETS, when it comes online in 2015, will be the second largest in the world.

Our findings also have implications for practitioners that are associated with the EU-ETS. For compliance buyers of carbon permits, who must trade in the market or reduce their emissions to avoid regulatory penalties, these results improve confidence in the EU-ETS. Compliance buyers can develop carbon trading strategies with better understanding of the market price evolution. This includes the distinctions between the different carbon futures instruments and the different trading periods and intervals. For investors, this study provides practical insights that can be useful for carbon investment strategies and effective risk management. Investor participation in the market requires the assurance of an appreciable level of price signalling. This is vital for efficient allocation of resources. By demonstrating that liquid carbon futures enjoy similar level of informational efficiency to traditional derivatives, our paper serves this purpose.

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**Table 1****Phases of the European Union Emissions Trading Scheme (EU-ETS)**

The table compares the three phases of the EU-ETS using regulatory issues as basis of comparison. Phase I spans between 2005 and 2007, Phase II started in 2008 and is expected to last till 2012 and Phase III starts in 2013 running until 2020.

<b>Variables</b>	<b>Phase I</b>	<b>Phase II</b>	<b>Phase III</b>
Gases targeted	CO <sub>2</sub> only	CO <sub>2</sub> only	CO <sub>2</sub> , Perfluorocarbons and Nitrous Oxide
Allocation system	Allocation based on grandfathering	Up to 10% of created permits can be auctioned	20% auctioning in 2013 with a gradual rise to 70% in 2020 (For power generators, full auctioning from 2013)
Proportion of GHG under scheme	40%	40%	50%
Banking regulations	Intra-phase banking only	Inter-phase banking allowed	Inter-phase banking
Allocation Planning	National Allocation Plans (NAP)	National Allocation Plans (NAP)	European Union-wide allocations
Penalty for default	€40 per missing EUA along with the submission of the subsequent missing EUA.	€100 per missing EUA along with the submission of the subsequent missing EUA.	Initial penalty per missing EUA is fitted to the European Price Index. The subsequent submission of the missing EUA is also expected.

**Table 2****Trading summary**

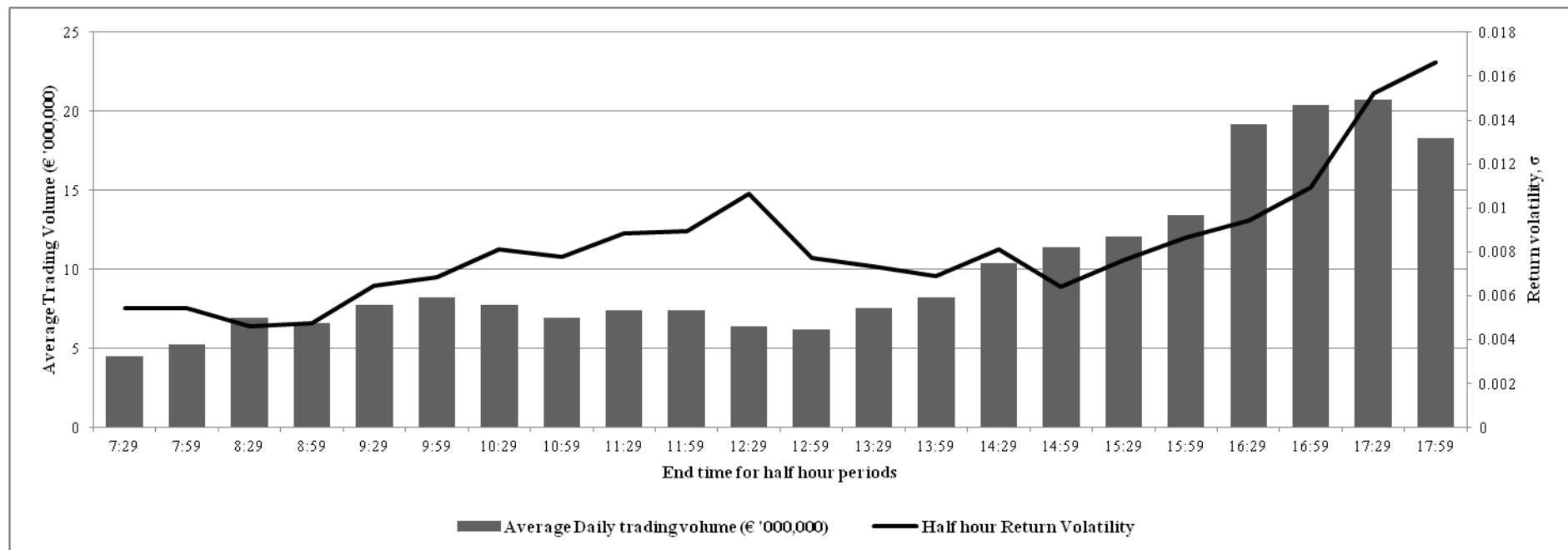
The table gives a summary of trading activities during After Market Closes (AMC) and normal trading day periods for four contracts trading on the European Climate Exchange (ECX) platform. The contracts are the highest volume trading ones of the contracts eligible for AMC trading. The data cover the trading period February 2009 through November 2009. The table includes estimates for daily average Euro volume, number of contract trades executed per day, average contract volume per day and percentage of days with trading for the AMC period. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.

	AMC				Normal Trading Day		
	Number of Trades	Volume (€ '000)	Contract Volume	% days with trading	Number of Trades	Volume (€ '000)	Contract volume
<b>Dec-09</b>	50.23	25907	1957.07	97.22	1239.61	129263	9775.74
<b>Dec-10</b>	5.66	4603	328.18	90.28	142.33	46571	1674.24
<b>Dec-11</b>	1.49	1916	131.03	63.89	52.51	19669	681.29
<b>Dec-12</b>	3.18	4214	267.79	79.63	84.65	19769	1279.83

**Figure 1**

**Trading Volume and Volatility**

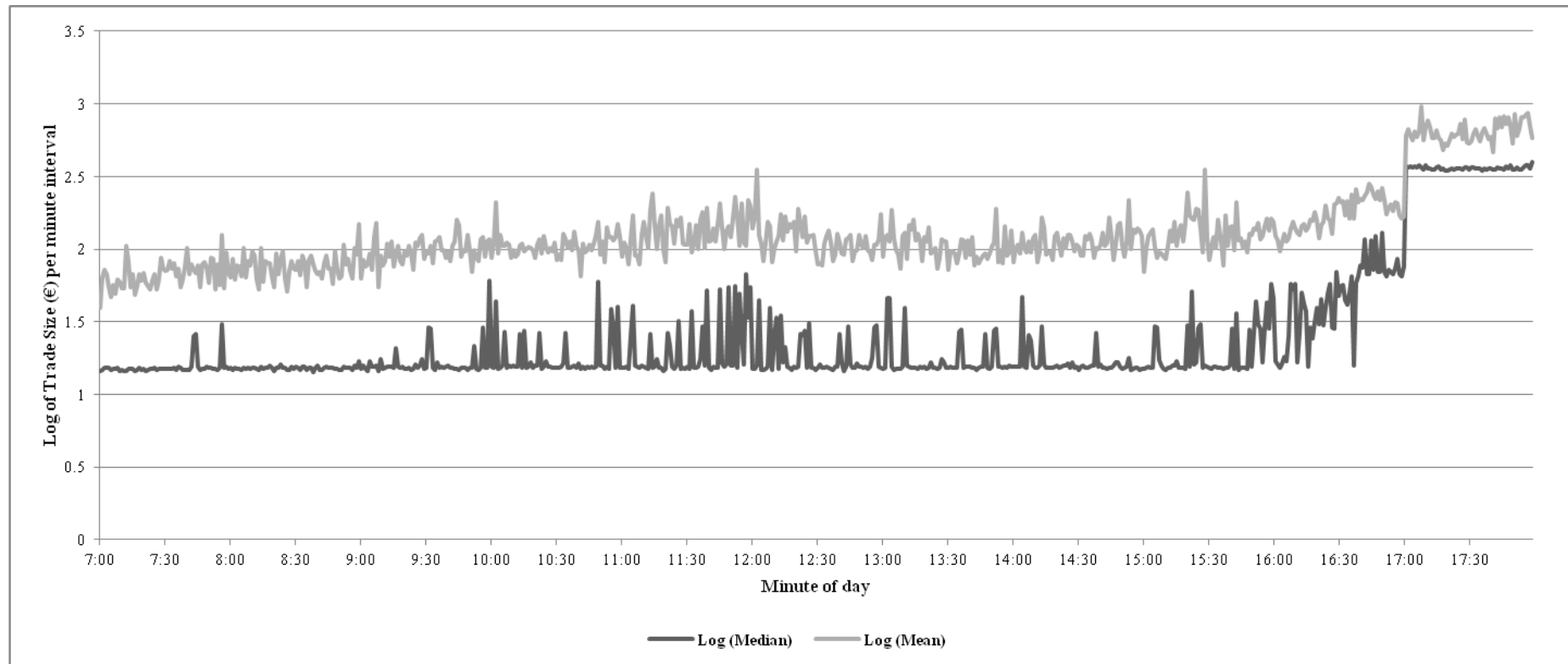
The figure shows average daily trading volume and volatility for every half-hour period of the normal trading day and After Market Closes (AMC) periods for four December maturity contracts (2009, 2010, 2011 and 2012) trading on the European Climate Exchange (ECX) platform. The data cover the trading period February 2009 through November 2009. Volatility is computed as the standard deviation of the half-hour contract return and is calculated for the December 2009 contract only due to large gaps in trading cycle of other contracts. We calculate volatility using the other contracts as well but excluding their trading gap periods and the results are highly similar. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.



**Figure 2**

**Log Median and Mean Trade Size**

The figure shows the logarithmic conversion of median and mean trade sizes over the entire trading periods of normal trading day and After Market Closes (AMC) for four December maturity contracts (2009, 2010, 2011 and 2012) trading on the European Climate Exchange (ECX) platform. The data covers the trading period February 2009 through November 2009. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.



**Table 3**

**Information Asymmetry And Half-Spread By Time Interval**

The table shows adverse selection costs components in Panel A and one-half effective spreads in Panel B for the four highest volume December maturity contracts on the European Climate Exchange (ECX) platform. Both the adverse selection costs components and the one-half spread components are estimated using the following contract specific model (Huang and Stoll, 1997):

$$\Delta P_{k,t} = \beta_{1,k} Q_{k,t} + \beta_{2,k} Q_{k,t-1} + \beta_{3,k} Q_{A,t-1} + e_t$$

where  $\Delta P_{k,t}$  is the change in price from the previous retained trade,  $Q_{k,t}$  is equal to 1 (-1) when the transaction at period t for contract  $k$  was a sell (buy) and  $Q_{A,t-1}$  is the aggregate buy-sell indicator variable used in

□ encapsulating portfolio trading pressure on market participants inventory levels, it equals 1(-1, 0) when the sum of  $Q_{k,t-1}$  across all four contracts is positive (negative, zero). Adverse selection costs component for each interval in Panel A is given as:

$$2(\beta_{2,k} + \beta_{1,k})$$

□ One-half effective spread for each interval in Panel B is given as  $\beta_{2,k}$ . Pairwise Wilcoxon-Mann-Whitney U tests are used to compute *p-values* for the differences between each of the different contract-dependent normal trading day intervals and the AMC period. In both panels, <sup>#</sup> denotes the normal trading day intervals during which the contract estimates are significantly different from the AMC. In Panel B, \* denotes statistical significance of the spread estimates at 1% level. The data covers the trading period February 2009 through November 2009. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time and the AMC runs between 17:00hrs and 18:00hrs London time.



Panel A: Adverse selection costs component

Time Periods							
Normal Trading Day						AMC	
Contracts	07:00-	09:00-	11:00-	13:00-	15:00-	07:00-	17:00-
	09:00	11:00	13:00	15:00	17:00	17:00	18:00
Dec-2009	0.016	0.036	0.012	0.001	0.002	0.014	0.411
Dec-2010	0.044	0.024	0.024	0.032	0.000	0.022	0.403
Dec-2011	0.049	0.083	0.047	0.028	0.032	0.053	0.511
Dec-2012	0.084	0.062	0.058	0.080	0.036	0.063	0.489
Overall	<b>0.048<sup>#</sup></b>	<b>0.051<sup>#</sup></b>	<b>0.035<sup>#</sup></b>	<b>0.035<sup>#</sup></b>	<b>0.017<sup>#</sup></b>	<b>0.038<sup>#</sup></b>	0.453

Panel B: One-half effective spread

Time periods							
Normal Trading Day						AMC	
Contracts	7:00-	9:00-	11:00-	13:00-	15:00-	07:00-	17:00-
	9:00	11:00	13:00	15:00	17:00	17:00	18:00
Dec-2009	0.026*	0.023*	0.025*	0.017*	0.017*	0.021*	0.235*
Dec-2010	0.045*	0.025*	0.032*	0.020*	0.018*	0.027*	0.239 *
Dec-2011	0.050*	0.057*	0.042*	0.038*	0.025*	0.041*	0.324 *
Dec-2012	0.072*	0.051*	0.083*	0.057*	0.038*	0.056*	0.348 *
Overall	<b>0.048<sup>#</sup></b>	<b>0.039<sup>#</sup></b>	<b>0.045<sup>#</sup></b>	<b>0.033<sup>#</sup></b>	<b>0.024<sup>#</sup></b>	<b>0.036<sup>#</sup></b>	0.286

**Table 4**

**Weighted Price Contribution by Time Intervals**

The table shows weighed price contribution (WPC) of six normal trading day intervals and the After Market Closes (AMC) period to the close-to-close return for the four highest volume December maturity contracts on the European Climate Exchange (ECX) platform. For each contract and interval  $k$  the weighed price contribution is computed for each day and then averaged across days:

$$WPC_{k,c} = \left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times \left( \frac{ret_{k,c}}{ret_c} \right)$$

Where  $ret_{k,c}$  is the log-return for interval  $k$  and for EUA contract  $c$ .  $ret_c$  is the close-to-close return for contract  $c$ . The trading days when close-to-close returns equal 0 are eliminated. The final column shows the fraction of days with close-to-close return equal to 0. The overall estimate in the final row is the sum of WPC for all contracts in that time interval. Wilcoxon-Mann-Whitney (tie-adjusted) tests are used to determine whether contract-dependent values for normal trading day intervals are significantly different from the AMC period. # denotes the contract-dependent normal trading day interval during which the contract WPC is significantly different from that of the AMC. \* indicates the WPC values significantly different from 0 at the 5% level. The data covers the trading period February 2009 through November 2009. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.

Time Periods								
Contracts	Normal Trading Day						AMC	Days with zero price change
	07:00-09:00	09:00-11:00	11:00-13:00	13:00-15:00	15:00-17:00	07:00-17:00	17:00-18:00	
Dec-2009	-0.006 <sup>#</sup>	-0.006	-0.02	-0.034	0.038	-0.028	0.003	0.019
Dec-2010	0.083 <sup>*#</sup>	0.038 <sup>#</sup>	-0.027	0.04	0.059 <sup>*#</sup>	0.193 <sup>*#</sup>	-0.028	0.019
Dec-2011	0.051	0.015 <sup>#</sup>	0.037 <sup>#</sup>	0.042	0.084 <sup>*</sup>	0.229 <sup>*</sup>	0.081 <sup>*</sup>	0.024
Dec-2012	0.084 <sup>*</sup>	0.072 <sup>*</sup>	0.029 <sup>#</sup>	0.026 <sup>#</sup>	0.109 <sup>*</sup>	0.32 <sup>*</sup>	0.23 <sup>*</sup>	0.019
Overall	0.212 <sup>*</sup>	0.119	0.019	0.074	0.29 <sup>*#</sup>	0.714 <sup>*#</sup>	0.286 <sup>*</sup>	0.019

**Table 5**

**Weighted Price Contribution Per Trade by Time Intervals**

The table shows weighed price contribution per trade (WPCT) of six Regular Trading Hours normal trading day intervals and the After Market Closes (AMC) period to the close-to-close return for the four highest volume December maturity contracts on the European Climate Exchange (ECX) platform. For each contract and interval  $k$  the weighed price contribution per trade is computed for each day and then averaged across days:

$$WPCT_{k,c} = \frac{\left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times \left( \frac{ret_{k,c}}{ret_c} \right)}{\left( \frac{|ret_c|}{\sum_{c=1}^C |ret_c|} \right) \times \left( \frac{t_{k,c}}{t_c} \right)},$$

$t_{k,c}$  is the number of executed trades in time interval  $k$  for contract  $c$ , and  $t_c$  is the total sum of  $t_{k,c}$  for all the intervals. The trading days when close-to-close returns equal 0 are eliminated. The final column shows the fraction of days with close-to-close return equal to 0. Wilcoxon-Mann-Whitney (tie-adjusted) tests are used to determine whether contract-dependent values for normal trading day intervals are significantly different from the AMC period. # denotes the contract-dependent normal trading day interval during which the contract WPCT is significantly different from that of the AMC. \* indicates the WPCT values significantly different from 0 at the 5% level. The data covers the trading period February 2009 through November 2009. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.

Time Periods								
Contracts	Normal Trading Day					AMC		Days with zero price change
	07:00-09:00	09:00-11:00	11:00-13:00	13:00-15:00	15:00-17:00	07:00-17:00	17:00-18:00	
Dec-2009	-0.12 <sup>#</sup>	-0.15	-0.57	-0.68	0.63	-0.12	0.31	0.019
Dec-2010	2.54 <sup>*#</sup>	0.76 <sup>#</sup>	-0.72	0.86 <sup>#</sup>	0.78 <sup>*#</sup>	0.80 <sup>*#</sup>	-2.90	0.019
Dec-2011	1.96 <sup>*</sup>	0.33	1.13 <sup>#</sup>	0.83 <sup>#</sup>	0.92 <sup>*</sup>	0.93 <sup>*</sup>	11.54 <sup>*</sup>	0.024
Dec-2012	2.78 <sup>*</sup>	1.75 <sup>*</sup>	1.04 <sup>#</sup>	0.63 <sup>#</sup>	1.10 <sup>*</sup>	1.34 <sup>*</sup>	25.53 <sup>*</sup>	0.019
Overall	1.79 <sup>#</sup>	0.67	0.22	0.41	0.86 <sup>*#</sup>	0.74 <sup>*#</sup>	8.63 <sup>*</sup>	0.019

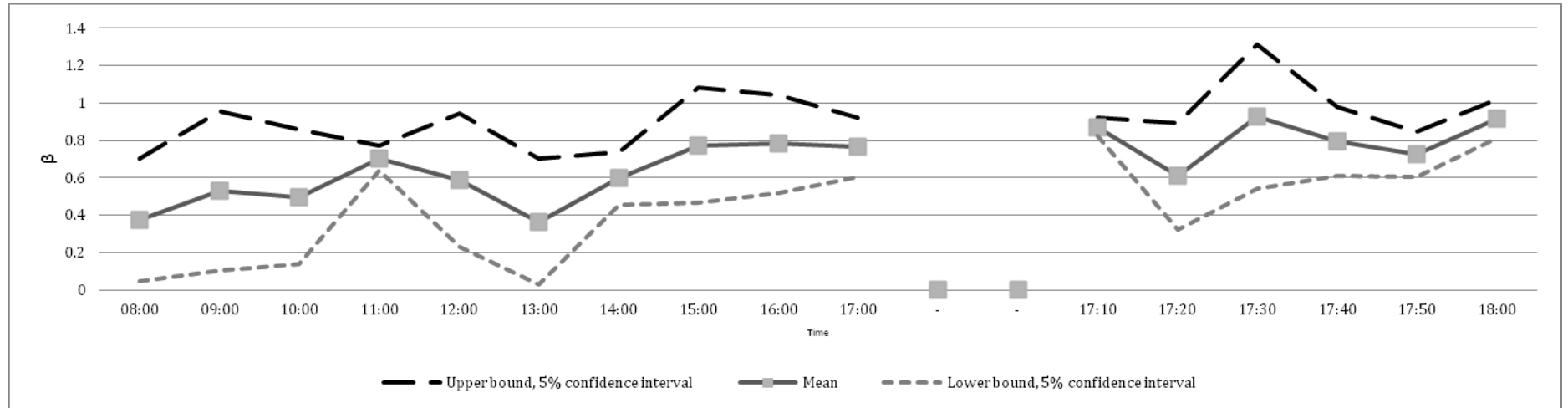
**Figure 3**

### Unbiasedness Regressions by intervals

The figure shows the chart of signal:noise ratio over the entire trading periods of normal trading day and After Market Closes (AMC) for the December maturity contracts (2009, 2010, 2011 and 2012) trading on the European Climate Exchange (ECX) platform. For each contract and each day, the following Equation is estimated separately for each time period (60 minutes each for the normal trading day and 10 minutes for the AMC), where  $ret_{cc}$  is the close to close return and  $ret_{ck}$  is the return from the close to the end time of period  $k$ . Confidence bands are computed using the time series' standard errors of the slope coefficient estimates.

$$ret_{cc} = \alpha + \beta ret_{ck} + \varepsilon_k$$

The data covers the trading period February 2009 through November 2009. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.



**Table 6**

**Unbiasedness Regressions by intervals**

The table shows results of signal:noise ratio over the entire trading periods of normal trading day (Panel A) and After Market Closes (AMC) (Panel B) for the December maturity contracts (2009, 2010, 2011 and 2012) trading on the European Climate Exchange (ECX) platform. For each contract and each day, the following Equation is estimated separately for each time period (60 minutes each for the normal trading day and 10 minutes for the AMC), where  $ret_{cc}$  is the close to close return and  $ret_{ck}$  is the return from the close to the end time of period  $k$ .

$$ret_{cc} = \alpha + \beta ret_{ck} + \varepsilon_k$$

\*\*\*, \*\*, \* denote the statistical significance of the coefficient estimates at 1%, 5% and 10% levels respectively. The last row shows the plotted mean coefficient estimates for the contracts. The data covers the trading period February 2009 through November 2009. The normal trading day period runs between 7:00hrs and 16:59:59hrs London time; the AMC runs between 17:00hrs and 18:00hrs London time.

Panel A: Normal Trading Day

Contracts		08:00	09:00	10:00	11:00	12:00	13:00	14:00	15:00	16:00	17:00
Dec-2009	Coefficient	0.85***	0.98***	0.75***	0.66***	1.01***	0.84***	0.71***	0.94***	0.85***	0.94***
	Std Error	0.099	0.082	0.082	0.081	0.067	0.066	0.052	0.044	0.047	0.024
	Adj. R <sup>2</sup>	0.26	0.41	0.28	0.24	0.50	0.44	0.47	0.69	0.61	0.88
Dec-2010	Coefficient	0.37***	0.82***	0.83***	0.80***	0.76***	0.36***	0.72***	0.86***	0.91***	0.86***
	Std Error	0.086	0.080	0.061	0.068	0.068	0.067	0.059	0.053	0.031	0.034
	Adj. R <sup>2</sup>	0.10	0.33	0.47	0.40	0.37	0.12	0.42	0.56	0.80	0.75
Dec-2011	Coefficient	0.09*	0.20***	0.38***	0.71***	0.37***	0.21***	0.42***	0.98***	0.97***	0.63***
	Std Error	0.049	0.063	0.074	0.064	0.065	0.061	0.062	0.044	0.040	0.056
	Adj. R <sup>2</sup>	0.01	0.04	0.11	0.36	0.13	0.05	0.17	0.70	0.74	0.38
Dec-2012	Coefficient	0.20***	0.12*	0.03**	0.65***	0.21***	0.05	0.55***	0.31***	0.39***	0.63***
	Std Error	0.043	0.065	0.0169	0.067	0.063	0.064	0.057	0.059	0.059	0.059
	Adj. R <sup>2</sup>	0.09	0.01	0.14	0.31	0.05	-0.0014	0.31	0.11	0.17	0.35
Overall		0.38	0.53	0.50	0.71	0.59	0.37	0.60	0.77	0.78	0.76
(Mean Coefficients)											

Panel B: AMC

Contracts		17:10	17:20	17:30	17:40	17:50	18:00
Dec-2009	Coefficient	0.87***	0.98***	1.51***	0.94***	0.91***	0.85***
	Std Error	0.065	0.047	0.043	0.048	0.046	0.054
	Adj. R <sup>2</sup>	0.46	0.68	0.74	0.64	0.65	0.54
Dec-2010	Coefficient	0.85***	0.67***	0.67***	0.78***	0.67***	0.88***
	Std Error	0.068	0.054	0.076	0.086	0.087	0.075
	Adj. R <sup>2</sup>	0.68	0.60	0.42	0.45	0.37	0.65
Dec-2011	Coefficient	0.95***	0.47***	0.85***	0.93***	0.70***	1.07***
	Std Error	0.170	0.083	0.120	0.071	0.172	0.067
	Adj. R <sup>2</sup>	0.48	0.49	0.58	0.83	0.30	0.92
Dec-2012	Estimate	0.83***	0.32***	0.68***	0.54***	0.63***	0.87***
	Std Error	0.093	0.082	0.082	0.084	0.077	0.089
	Adj. R <sup>2</sup>	0.58	0.18	0.51	0.37	0.47	0.68
Overall (Mean Coefficients)		0.87	0.61	0.93	0.80	0.73	0.92

## Appendix

### ECX EUA Futures Contract specification

<b>Unit of Trading</b>	One lot of 1,000 emission allowances (i.e. 1,000 tonnes of CO <sub>2</sub> )
<b>Quotation</b>	Euro (€) and Euro cent (c) per metric tone
<b>Tick</b>	€0.01
<b>Contract months</b>	Contracts are listed on a quarterly expiry cycle such that March, June, September and December contract months are listed up to December 2012 (Annual contracts with December expiries for 2013 and 2014 as well as March 2013 are available for only EUA contracts)
<b>Contract security</b>	ICE CLEAR EUROPE guarantees the financial performance of ICE Futures Europe contracts registered in the name of its members
<b>Trading system</b>	Trading will occur on the ICE Futures Europe platform accessible via Web ICE, or through a conformed Independent Software Vendor
<b>Trading model</b>	Continuous trading between 07:00 hours to 17:00 hours UK local time
<b>Settlement Prices</b>	Trade weighted average during the daily closing period with Quoted Settlement Prices if low liquidity
<b>Delivery</b>	The Contracts are physically deliverable by the transfer of emissions allowances. There is a delivery period of 3 days after the last day of trading